Looking for systematic error in scale from terrestrial reference frames derived from DORIS data

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Abstract

The long-term stability of the scale of Terrestrial Reference Frames is directly linked with station height determination and is critical for several scientific studies, such as global mean sea level rise or ocean circulation with consequences on global warming studies. In recent International Terrestrial Reference Frame (ITRF) solutions, the DORIS technique was not considered able to provide any useful information on scale (derived from VLBI). We have analyzed three different DORIS time series of coordinates (GSFC, IGN/JPL, LEGOS/CLS) performed independently using different software packages. On the long-term, we show that the DORIS technique, due to its very stable and geographically distributed network, has extremely good stability (<0.1 ppb/yr). In the short-term, the three groups show systematic errors in scale (up to 5 ppb) that could come from their specific analysis strategies. Furthermore, we have investigated on a shorter time period (2004) new results for single-satellite solutions. This analysis is a first step in understanding the systematic errors currently seen in the DORIS-derived scale from different groups.

Keywords. DORIS, Terrestrial Reference Frame (TRF), orbit determination, systematic errors

1 Introduction

Several key geophysical studies, such as global change, plate tectonics, or post-glacial rebound cannot be done without a proper geodetic frame. Recently, the International Association of Geodesy (IAG) has started an ambitious project called Global Geodetic Observing System (GGOS) in order to serve as a backbone infrastructure for other geosciences, see Rummel et al., 2002. In particular the definition and the maintenance of the Terrestrial Reference Frame (TRF) is a key component of this proposal, see Altamimi et al., 2005.

Let us briefly redefine the mathematical relationships relating two TRFs. Equation (1) describes the 14-parameter simplified conformal transformations between those TRFs when the same reference epoch is used for all station coordinates and data sets.

$$\begin{cases} X_j = X_0 + T_j + s_j X_0 + R_j X_0 \\ \dot{X}_j = \dot{X}_0 + \dot{T}_j + \dot{s}_j X_0 + \dot{R}_j X_0 \end{cases} \quad (1)$$

Where X_j (resp. $\dot{X}_j$) is the matrix of station coordinates (resp. velocities) of the j^{th} data set (in our case, GSFC, IGN/JPL or LEGOS/CLS), and X_0 (resp. $\dot{X}_0$) is the matrix corresponding to the reference data set (ITRF2000, see Altamimi et al., 2002). The transformation parameters and their time derivatives between the j[th] data set and the reference data set are the matrices T_j (resp. $\dot{T}_j$) for translation, R_j (resp. $\dot{R}_j$) for translation and the scale factor s_j (resp. $\dot{s}_j$).

In principle the scale factor s is small (up to a few ppb for recent realizations derived from space geodetic techniques) but it must noted that a 1 ppb systematic error in the TRF scale is rather small as it is equivalent to a constant systematic error of 6.4 mm for all station height. A 0.1 ppb systematic error in the scale factor derivative is therefore only equivalent to a 0.64 mm/yr systematic error in station vertical velocities or any derived geophysical product, such as global mean sea level rise (Morel and Willis, 2005). On the other hand, these numbers may be seen as too large for oceanographers investigating small long-term variations in mean sea level (Cazenave and Nerem, 2004).

The DORIS system (Doppler Orbit determination and Radiopositioning Integrated on Satellite) is one of the contributing techniques with GGOS whose activity is organized since 2003 within the International DORIS Service (IDS), (Tavernier et al., 2005).

It can be seen on Figure 1 that the DORIS technique possesses a rather dense and geographically well-distributed tracking network, potentially well suited for TRF maintenance. In January 2005, 48 DORIS tracking beacons were observing on a permanent basis.

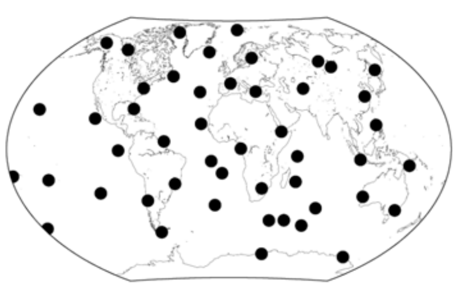

Fig. 1 DORIS permanent tracking network (January 2005).

Since 1990, several satellites have been launched and carry an on-board DORIS receiver, see Table 1. The best geodetic results are obtained when using DORIS data from all satellites, see Willis et al., 2005a or Tavernier et al., 2005.

Table 1. List of satellites currently carrying a DORIS receiver (July 2005)

Satellite	Launch	Altitude (km)
SPOT-2	Jan 1990	830
SPOT-3	Mar 1994	830
SPOT-4	July 1998	830
Jason-1	Dec 2001	1,330
ENVISAT	Mar 2002	800
SPOT-5	May 2002	830

In this study, we have considered solutions derived by three different DORIS Analysis Centers (ACs) using three different software packages to investigate possible systematic errors in their realization of the TRF and more specifically of the TRF scale factor. In particular, we would like to assess the accuracy of the derived scale factor and to investigate if some DORIS results could be use in the future to define the scale of the ITRF2004.

2 Terrestrial reference frame scale factor derived from station coordinates

2.1 Description of the considered DORIS weekly TRF solutions

In this study, we considered solutions from three different ACs, all using the DORIS preprocessed data available at CDDIS:

(1) The Goddard Space Flight Center (GSFC)NASA used the GEODYN software package (version 0407) (Lemoine et al., 1998).

(2) The *Institut Geographique National* (IGN), France in common with Jet Propulsion Laboratory (JPL) used the Gipsy/Oasis II software package (Webb and Zumberge, 1995; Willis et al., 2005a).

(3) The *Laboratoire d'Etudes en Geophysique et Oceanographie Spatiale* (LEGOS) in conjunction with *Collecte Localisation par Satellite* (CLS) used the GINS/DYNAMO II (version 0407) software package (Cretaux et al.1998; Soudarin et al., 1999).

All groups used their current analysis strategy. No attempt was made to use exactly the same models or processing strategies to minimize possible systematic errors. In particular different gravity fields were used, all based on recent GRACE data, see Tapley et al., 2004: GGM02C (120x120, including C20-dot, C21-dot and S21-dot) for GSFC, GGM01C (120x120) for IGN/JPL and GRIM5-C1 (120x120, truncated at degree 90 for ENVISAT and SPOTs and 75 for TOPEX) (Biancale et al., 2000). In most cases, the use of the recent GRACE-derived gravity field provided enhanced DORIS geodetic results (Willis and Heflin, 2004, Feissel-Vernier et al., 2005)

DORIS data were processed using 7-day arcs for GSFC, 1-day arcs for IGN/JPL and 3.5-day arcs for LEGOS/CLS.

Atmospheric density models used were MSIS86 for GSFC and DTM94 for IGN/JPL and LEGOS/CLS. Additional drag parameters were estimated every 6-hr (resp. 8-hr) for ENVISAT and SPOT5 (resp. T/P, SPOT2 and SPOT4) by GSFC. Drag parameters were estimated every 6-hr for ENVISAT and SPOTs by IGN/JPL and LEGOS/CLS, while estimated every 12-hr for T/P only by LEGOS/CLS, as using longer arcs.

Center of mass corrections were recomputed by GSFC, used from CNES preprocessed data files by IGN/JPL and computed by LEGOS for TOPEX and SPOTs before September 2004 or otherwise used from the data files.

All ACs estimated tropospheric corrections per satellite pass but IGN/JPL used a more sophisticated approach, adding time-dependant constrains between passes, (Willis et al., 2005a).

Atmospheric pressure loading corrections were used by LEGOS/CLS but not by IGN/JPL, potentially leading to small TRF effects, (Tregoning et al., 2005). GSFC does not apply atmospheric loading – geometric station correction but uses a dynamical correction to the geopotential coefficients to model atmospheric mass variations (Chao and Au, 1991).

GSFC (resp. LEGOS/CLS) used a common a priori data weigh of 0.5 mm/s (resp. 0.4 mm/s) for DORIS Doppler measurement, while IGN/JPL used 0.4 mm/s for SPOT5 (newer generation) and 0.5 mm/s for all others.

GSFC (resp. LEGOS/CLS) preprocessed the DORIS data using a 5-degree (resp. 4-degree) minimum elevation cut-off angle, while IGN/JPL used all available data.

Finally, the DORIS data from Jason-1 satellite were not used in this study due to unexpected large sensitivity to radiation leading to erroneous clock accelerations over the South Atlantic Anomaly (SAA), (Willis et al., 2004). Fortunately, Jason-1 orbit results are less affected, especially when derived using simultaneously GPS, DORIS and Laser data (Luthcke et al., 2003

2.2 Using multi-satellite solutions

As a first step, we have compared weekly station coordinates using all available DORIS data (except Jason-1) from January to December 2004 with a unique reference based on ITRF2000 (Altamimi et al., 2002), on a week-by-week basis and on a AC-by-AC basis using the standard projection and transformation approach, (Sillard and Boucher, 2001).

Figure 2 shows that the weekly TRF scale factors are very different from one group to another. The IGN/JPL provides smaller values (typically -3 ppb) while GSFC and LEGOS/CLS provide slightly larger values (typically +5 ppb) but in good agreement for the first 6 months.

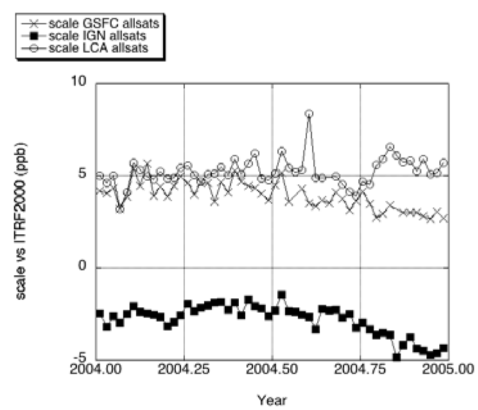

Fig. 2 Weekly scale factor determination towards ITRF2000 using multi-satellite SINEX solutions. GSFC (white circle), IGN/JPL (black squares), LEGOS/CLS (crosses). January – December 2004.

The IGN/JPL solution also provides a more consistent time series as easily detected by an Allan Variance test: 0.168 ppb^2 for IGN/JPL, 0.427 $ppb^2$for LEGOS/CLS and 0.665 ppb^2 for GSFC.

It must be noted that the GSFC and the LEGOS/CLS solutions tend to diverge around September 2004, when LEGOS/CLS changed their strategy to use the phase center corrections directly from the DORIS data files instead of re-estimating them. This could be a valuable information to understand how analysis strategies can lead to systematic errors in scale factor determination. Some future tests of this type will be needed.

To be more specific, we tried to use different references to do these comparisons, either using directly ITRF2000 (with less points in common as the DORIS tracking network has evolved between the end of 2000 and 2004, see Willis and Ries, 2005), or using differenet internal AC-derived solutions based on the 2004 data and transformed into ITRF2000, or even using a unique long-term cumulative DORIS solution (based on more than 10 years of observations and including all 2004 DORIS stations), such as IGN04D02, (Willis et al., 2004). All comparisons led to similar results (differences were less than 0.1 ppb) for each weekly determination of the scale factor.

2.3 Using single-satellite solutions

In the second stage of our analysis, we have done the same type of study but using DORIS single-satellite weekly solutions. These solutions are, of course, noisier (based on lesser data) but we think that these comparisons could better help us identify some satellite-related systematic errors.

For TOPEX/Poseidon (T/P), GSFC and LEGOS/CLS show a good internal agreement and also a good agreement with ITRF2000 (see Figure 3). There is again a systematic difference of -2 ppb between the IGN/JPL and the two other solutions. No results are available after November 1, 2004 as the DORIS receiver on-board T/P unfortunately stopped functioning after 13 years of continuous operation.

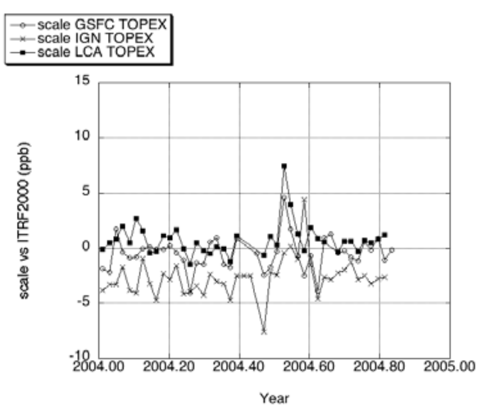

Fig. 3 Weekly scale factor determination towards ITRF2000 using TOPEX/Poseidon SINEX solutions. GSFC (white circles), IGN/JPL (black squares), LEGOS/CLS (crosses). January – December 2004.

SPOT2 and SPOT4 provide similar results (Figure 4 for SPOT2). On Figure 4, a possible discontinuity may be observed in fall 2004 for the IGN/JPL SPOT2 results. This discontinuity is not observed at all by the other centers.

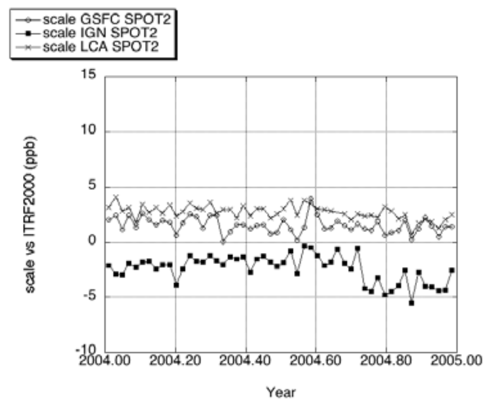

Fig. 4 Weekly scale factor determination towards ITRF2000 using SPOT2 SINEX solutions. GSFC (white circles), IGN/JPL (black squares), LEGOS/CLS (crosses). January – December 2004.

Finally, SPOT5, equipped with a newer type of instrument (second generation, see Tavernier et al., 2005) provides more consistent results (Figure 5), especially for the IGN/JPL solution. The GSFC and LEGOS/CLS scale are still very close but far away from the ITRF2000 reference (+7 ppb). Some additional tuning may be required by the different ACs for processing data from this recent satellite.

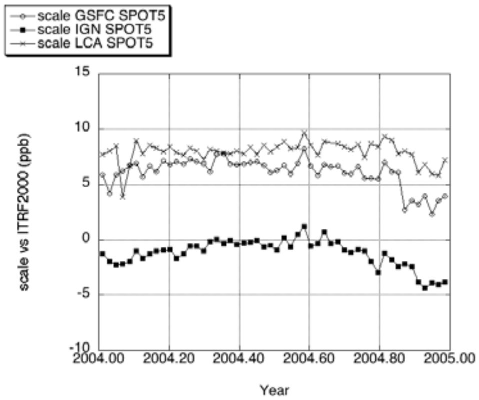

Fig. 5 Weekly scale factor determination towards ITRF2000 using SPOT5 SINEX solutions. GSFC (white circles), IGN/JPL (black squares), LEGOS/CLS (crosses). January – December 2004.

In the case of ENVISAT, a similar pattern can also be found. The GSFC and the LEGOS/CLS solutions are still very close but far apart from ITRF2000 (around +8 ppb). In the second half of 2004, all 3 solutions show an interesting pattern that could be linked to a possible annual signal or long-term oscillation. This could be an indication of remaining orbit errors. This is not surprising for such a large and complex satellite, orbiting at a lower orbit with such a complex shape.

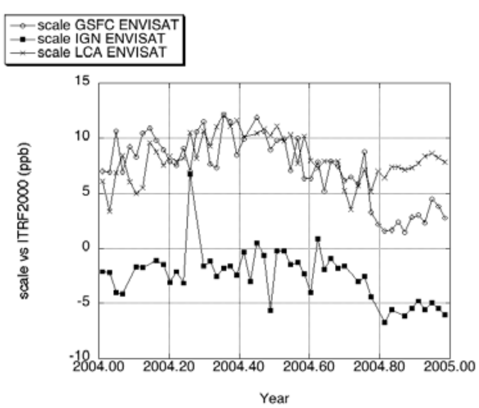

Fig. 6 Weekly scale factor determination towards ITRF2000 using ENVISAT SINEX solutions. GSFC (white circles), IGN/JPL (black squares), LEGOS/CLS (crosses). January – December 2004.

In summary, Figures 2 to 6 show that the IGN/JPL solution is always close to a constant value (with an -3 ppb offset from ITRF2000), while the GSFC and the LEGOS/CLS show larger satellite-dependant biases, especially for the newer satellites such as SPOT5 and ENVISAT, for which improved satellite orbits can still be found. In our opinion, this may explain why the IGN/JPL multi-satellite solution showed a better internal consistency (Allan variance) as it presents smaller satellite-dependant biases.
However, some clear long-term signals are also clearly visible in the results. They could be attributed to annual variations potentially due to mis-modelled atmospheric effects (ionosphere correction?). Several sources of annual systematic errors can be found in geodetic results (Cretaux et al., 2002; Meisel et al., 2005). The present analysis, limited to the 2004, is not sufficient to fully answer these questions.
If we assume that the DORIS scale factor can be modeled as a constant systematic bias per AC and per satellite, we can derive the following synthetic results (Table 2).

Table 2. Terrestrial reference frame scale factor derived from station coordinates. Mean and standard deviation estimated for different Analysis Center. January – December 2004. Part per Billion (ppb)

Satellite	GSC	IGN	LCA
SPOT2	1.5 ± 0.7	-2.4 ± 1.2	2.7 ± 0.7
SPOT4	2.4 ± 0.9	-1.9 ±1.1	3.4 ± 0.6
SPOT5	6.1 ± 1.3	-1.2 ± 1.2	8.1 ± 1.0
T/P	-0.5 ± 1.5	-2.7 ± 1.7	0.8 ± 1.5
ENVIS	7.2 ± 3.1	-2.5 ± 2.4	8.2 ± 2.1
All sats	4.0 ± 0.7	-2.8 ± 0.8	5.2 ± 0.8

Table 2 shows that IGN/JPL shows smaller inter-satellite biases. However, GSFC and LEGOS/CLS shows smaller biases toward ITRF2000 for the older satellites (SPOT2, SPOT4 and TOPEX).

2.4 Testing long-term stability of TRF scale bias

In parallel, we have combined all weekly DORIS IGN/JPL sinex solutions available from 1993.0 to 2005.25 to create a refined DORIS cumulative

solution (Willis et al, 2005a, Willis and Ries, 2005). DORIS station positions and velocities were all estimated simultanesoulsy, DORIS-DORIS geodetic local ties were also used with proper weighting. This can be considered as an updated solution of the IGN/JPL latest cumulative solution available at NASA/CDDIS data center (IGN04D02, see Willlis et al, 2005a).
A direct comparison between this frame and the ITRF2000, provided the following results for the TRF scale:

$$scale(2000.0) = -3.12 \pm 0.54\, ppb \qquad (2)$$

$$scale\_rate = -0.075 \pm 0.046\, ppb / yr \qquad (3)$$

These results confirm the -3 ppb bias previously observed for the IGN/JPL solutions for all satellites. They also show an extremely good long-term agreement with the ITRF2000 (better than 0.1 ppb for the formal error and for a potential bias). These numbers confirm earlier determination of this stability (Willis et al., 2005b).
If needed, we could use a time-limited subset of the DORIS data to recalibrate the satellite antenna offsets (center of phase of the antenna - center of mass), as currently done by the GPS ACs, to be align the TRF scale on ITRF2000. Using these new empirical values would ensure a long-term consistency with ITRF2000 at the 1ppb level for almost 2 decades (from Eq. 3). At present, no DORIS AC plans to follow such a path. At least, more investigation is required to better understand the sources of errors in DORIS data processing potentially leading to systematic errors in the TRF scale.

3 Terrestrial reference frame scale factor derived from satellite orbits

In a second step, we have compared satellite orbits provided by each AC in 2004, fixing all DORIS station coordinates to ITRF2000 values. All satellites orbits were computed individually using only DORIS data. Comparisons were only performed for the ENVISAT satellite as it showed larger discrepancies in earlier tests discussed here.
Table 4 shows the consistency between orbits from different solutions. As expected, best results are obtained in the radial component leading to 1-2 cm differences in RMS between all groups. No bias could be found in the radial and cross-track component (less than a couple of mm). However, a significant bias could be found for the IGN/JPL group in the along-track component (-10 cm) towards the 2 other group. Such a problem is potentially related to time tagging issues either in the measurement modeling or in the orbit file results.

Table 3. ENVISAT orbit comparisons (January – December 2004) between ACs (GSC = GSFC, IGN = IGN/JPL, LCA = LEGOS/CLS), Daily Root mean squares in the radial, cross-track and along-track component.

	radial	cross	along
LCA-IGN	1-2 cm	6-8 cm	11-14 cm
GSC-IGN	1-2 cm	4-10 cm	10-12 cm
GSC-LCA	1-2 cm	4-10 cm	3-6 cm

It can be seen that even if the 3 ACs have estimate different TRF scales that could differ by almost 10 ppb, the derived orbits do not present a systematic error in the satellite altitude. This result was predictable, looking at earlier simulation results (Morel and Willis, 2005), as the satellite period is directly accessible from the observations and as the 3rd keplerian law directly links the satellite orbit period to the semi-major axis of the orbit (and then to the orbit radial error).
In the case of the ENVISAT satellite, orbits can be tested using external sources of information, such as Laser residuals. These tests were done at GSFC using the GEODYN software and are displayed in Table 4.

Table 4. ENVISAT mean Laser residuals over 2004.

	All	High elev (>70 deg)
GSFC	5.6 cm	2.7 cm
IGN/JPL	9.6 cm	3.6 cm
LEGOS/CLS	4.9 cm	3,2 cm

Typically over 50000 laser residuals were tested for ENVISAT in 2004 (56484 for GSFC, 51623 for IGN/JPL and 47693 for LEGOS/CLS). In order to better test the radial component a sub-category was also analyzed, selecting only Laser residuals at high elevation (over 70 degrees). This sub-set already comprises a lot of data

points: 1347 for GSFC, 1248 for IGN/JPL and 1141 for LEGOS/CLS.
It can be seen that GSFC and LEGOS/CLS provide better results in all cases and especially when all residuals are considered (high and low elevation together). However, in the case of the IGN/JPL solution, the Laser residual test could be altered by the constant along-track offset previously detected. High elevation Laser residuals would be not be affected by a timing error but all other Laser residuals would be.

Conclusions

In order to investigate the stability of the DORIS-derived terrestrial reference frame scale factor, we have analyzed weekly station coordinates and daily orbits obtained by three different groups using three different software and analysis strategies (GSFC, IGN/JPL and LEGOS/CLS).
Results show that the TRF scale derived by all groups are affected by satellite-dependent biases, even if the IGN/JPL solution seems to be less affected. Typically single satellite TRF solutions can show biases in scale up to almost 10 ppb. However, multi-satellite DORIS solutions show a better agreement with ITRF2000 (typically up to 5 ppb). However, DORIS provides an excellent long-term stability for scale monitoring (typically 0.05 ppb/yr).
Preliminary tests on ENVISAT orbit show a 10 cm mis-modelling bias in the along-track component that could also be linked with timing issues.
In order to better understand these systematic errors, future tests are needed in which all groups try to use the same analysis strategy. With the recent creation of the International DORIS Service, we hope that future Analysis Centers will join in to perform these tests and discuss these difficult issues.

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References

Altamimi, Z., P. Sillard, C. Boucher (2002). ITRF2000, A new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research*, Solid Earth, vol. 107(B10), 2214.

Altamimi Z., C. Boucher, P. Willis (2005). Terrestrial Reference Frame requirements within GGOS, *Journal of Geodynamics.*

Biancale R., G. Balmino, J.M. Lemoine, et al. (2000). A new global Earth’s gravity field model from satellite orbit perturbations, GRIM5-S1, *Geophysical Research Letters*, Vol. 27(22), pp. 3611-3614.

Cazenave A., R.S. Nerem (2004). Present-day sea level change, Observations and causes, *Reviews of Geophysics*, Vol. 42(3), RG3001.

Chao B.F., amd A. Au (1991), Temporal variation of the Earth’s low-degree field caused by atmospheric mass redistribution – 1980-1988, *Journal of Geophysical Research*, Solid Earth, Vol. 96(B4), pp. 6569-6575.

Crétaux J.F., L. Soudarin, A. Cazenave, F. Bouille (1998), Present-day Tectonic Plate Motions and Crustal Deformations from the DORIS Space System. *Journal of Geophysical Research*, Solid Earth vol. 103(B12), pp. 30167-30181.

Crétaux J.F., L. Soudarin, F.J.M. Davidson, M.C. Gennero, M. Berge-Nguyen, A. Cazenave (2002), Seasonal and interannual geocenter motion from SLR and DORIS measurements, comparison with surface loading data, *Journal of Geophysical Research*, Solid Earth, Vol. 107(B12), 2374.

Feissel-Vernier M., J.J. Valette, K. Le Bail, L. Soudarin (2005). Impact of the GRACE gravity fields models on IDS products, *International DORIS Service Report*.

Lemoine F.G., et al. (1998). The development of the joint NASA/GSFC and the National Imagery and mapping Agency (NIMA) geopotential models, EGM96, in NASA, TP-1998-206861, pp. 1-575.

Luthcke S.B., N.P. Zelensky, D.D. Rowlands, F.G. Lemoine, T.A. Williams (2003). The 1-centimeter orbit, Jason-1 precision orbit determination using GPS, SLR, DORIS, and altimeter data, *Marine Geodesy*, Vol. 26(3-4), pp. 399-421.

Meisel B, D. Angermann, M. Krugel, H. Drewes, M. Gerstl, R. Kelm, H. Muller, W. Seemuller, V. Tesmer (2005). Refined approaches for terrestrial reference frame computations, *Advances in Space Research,* DOI: 10.1016/j.asr.2005.04.057.

Morel L., and P. Willis (2005). Terrestrial reference frame effects on mean sea level rise determined by TOPEX/Poseidon, *Advances in Space Research*, DOI: 10.1016/j.asr.2005.05.113.

Rummel R., H. Drewes, G. Beutler (2002). Integrated Global Observing System IGGOS, A candidate IAG Project, In Proc. *International Association of Geodesy*, Vol. 125, pp. 135-143.

Sillard P., and C. Boucher (2001). A review of algebraic constraints in Terrestrial Reference Frame datum definition, *Journal of Geodesy*, Vol. 75(2-3), pp. 63-73.

Soudarin L., J.F. Crétaux, A. Cazenave (1999). Vertical Crustal Motions from the DORIS space-geodesy system, *Geophysical Research Letters*, Vol. 26(9), pp. 1207-1210.

Tapley B.D., S. Bettadpur, M. Watkins, C. Reigber (2004), the Gravity Recovery and Climate Experiment, Mission overview and early results, *Geophysical Research Letters*, Vol. 31(9), L09607.

Tavernier G., H. Fagard, M. Feissel-Vernier, F. Lemoine, C. Noll, J.C. Ries, L. Soudarin, P. Willis (2005). The International DORIS Service, IDS. *Advances in Space Research*, DOI: 10.1016/j.asr.2005.03.102.

Tregoning P., T. van Dam (2005). Effects of atmospheric pressure loading and seven-parameter transformations on estimates of geocenter motion and station heights from space geodetic observations, *Journal of Geophysical Journal*, Solid Earth, Vol. 110(B3), B03408.

Webb F., and J. Zumberge (Eds.) (1995). An introduction to Gipsy/Oasis II, *Report Jet Propulsion Laboratory*, Pasadena, USA, JPLM D-11088.

Willis P., and M. Heflin (2004), External validation of the GRACE GGM01C Gravity Field using GPS and DORIS positioning results, *Geophysical Research Letters*, Vol. 31(13), L13616.

Willis P., and J.C. Ries (2005), Defining a DORIS core network for Jason-1 precise orbit determination based on ITRF2000, methods and realization. *Journal of Geodesy*, DOI: 10.1007/s00190-005-0475-9

Willis P., B. Haines, J.-P. Berthias, P. Sengenes, J.L. Le Mouel (2004), Behavior of the DORIS/Jason oscillator over the South Atlantic Anomaly. *Comptes Rendus Geoscience*, Vol. 336(9), pp. 839-846.

Willis P., C. Boucher, H. Fagard, Z. Altamimi (2005a). Geodetic applications of the DORIS system at the French Institut Geographique National. *Comptes Rendus Geoscience*, Vol. 337(7), pp. 653-662.

Willis P., Y.E. Bar-Sever, G. Tavernier (2005b), DORIS as a potential part of a Global Geodetic Observing System. *Journal of Geodynamics*, in press.